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LCA FOR AGRICULTURE

Carbon balance impacts of land use changes related to the life cycle of Malaysian palm oil-derived biodiesel

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Abstract

Purpose The area of oil palm plantations in Malaysia is expanding by approximately 0.14 million hectare per year, and with the increasing demand for palm oil worldwide, there is no sign of the expansions slowing down. This study aims to identify the greenhouse gas emissions associated with land conversion to oil palm, in a life cycle perspective.

Methods LCA methodology is applied to existing land use change data. The assessment includes the issue of temporary carbon storage in the plantations. Through quantification of emissions from state forest reserve and rubber plantation conversions, the average Malaysian palm oil-related land use changes are calculated.

Results and discussion The results show that there are high emissions associated with the conversion of Malaysian state forest reserve to oil palm, whereas the conversion of rubber leaves a less significant carbon debt when indirect land use change is not included. Looking at the average Malaysian land use changes associated with oil palm shows that land use change emissions are responsible for approximately half of the total conventional biodiesel production emissions. The sensitivity analysis shows that the results could be significantly influenced by data variations in indirect land use changes, peat soils, and state forest reserve carbon stock.

Conclusions The relatively extensive conversions of the state forest reserve must be reversed and preferably with a shift toward conversion of degraded land in order for the average Malaysian land use changes to have less impact on the production life cycle of palm oil and biodiesel.

Keywords Biodiesel · Forest · Land use change · LUC · Palm oil · Plantations · Rubber · Temporary carbon storage

1 Introduction

Oil palm plantations cover 4.98 million hectares (ha) in Malaysia in 2011, which is 15 % of the total land area. In the past 25 years, which is the length of an oil palm cycle, the area has increased by 3.4 million ha at a relatively consistent 0.14 million ha per year (MPOB 2012). Palm methyl ester (PME) is biodiesel produced from palm oil, and the production is on the rise, thus furthering the expansion of oil palm plantations. The conversion of land to oil palm plantations can result in significant greenhouse gas (GHG) emissions, especially if forest is converted to plantation, which can negate the benefits of PME produced from palm oil (Kim et al. 2009). Some studies exist, which quantify the emissions from land use change (LUC) in relation to palm oil. Reijnders and Huijbregts (2008) used LUC data in their environmental assessment of palm oil, while arguably, the most comprehensive review on palm oil-related LUC is conducted by Germer and Sauerborn (2008), who include biomass as well as soil carbon estimates. In the data discussions in Sections 3.1.1, 3.1.2, 3.1.3, 3.1.4, and 3.1.5, more palm oil-related LUC references are presented. The existing studies have all considered the

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results of converting a single previous land use to oil palm, e.g., Wicke et al. (2008). A study of the Malaysian average LUC GHG emissions related to palm oil has not been previously published.

PME is a direct derivative of palm oil in line with numerous other palm oil uses, and the expansion of oil palm plantations in Malaysia can be assumed to result in LUC from the prevailing marginal land independent of the use of the palm oil. The net overall emissions from Malaysian palm oil-related LUC are therefore independent from which land is used for PME and which land is use for other palm oil products. Thus, in line with life cycle assessment (LCA) methodology, e.g., Finnveden et al. (2009), it is argued in this study that whether PME is produced from a plantation on former state forest, rubber, or other land use, the average Malaysian LUC values should be used to assess the sustainability of the PME.

Whereas existing studies (except Reijnders and Huijbregts 2008) have not distinguished between permanently stored/fossil carbon and temporarily stored/biogenic carbon and thus generated result in which the two types of carbon are directly comparable, this study focuses on introducing this distinction to the case of palm oil-related LUC (see Section 2.1).

Figure 1 illustrates that oil palm plantations have primarily been planted on the state forest reserve and rubber plantations in the past 25 years (from FAO (2010); MPOB (2012); (MRB 2011)). State forest reserve is forest earmarked by the Malaysian Government for the development (Woon and Norini 2002), from which large trees have been or will be harvested for timber, but with smaller trees and undergrowth still standing until the land is cultivated. As land from other land uses such as rubber, coconut, cocoa, and other fruits have become sparser, conversion from the state forest reserve has become more dominant in the past 10 years. Thus, this study focuses primarily on the conversion from state forest reserve and from rubber plantations with other land uses included qualitatively.

In this study, the GHG emissions related to LUC from conversion of the state forest reserve, rubber and the Malaysian average LUC emissions are put in a life cycle perspective for PME production, and related to the PME production emissions presented in Hansen et al. (2012), which does not include LUC. In order to relate the total GHG emissions from PME production to a tangible reference, the final emissions are compared to the emission requirements of the European Union Renewable Energy Directive (EU-RED), which dictates that renewable energy must provide at least 35 % reduction in GHG emissions compared to its fossil counterpart (European 2009).

As reference to Hansen et al. (2012) is given extensively in this paper in order to include LUC in a life cycle perspective for the production of palm oil, some key aspects from Hansen et al. (2012) are given here: The paper presents GHG emissions and savings from conventional residue uses and potential energy recovery uses in the Malaysian palm oil industry. A scenario estimating the conventional uses for the various residues and the resulting GHG emissions was set up. A similar scenario was created, assuming full use of the residues for energy recovery purposes and subsequent substitution of fossil fuels (“improved residue use”). The results showed that the conventional residue use/disposal is emitting almost 1,000 kg CO_2-eq per ton of PME produced, whereas the improved residue use can potentially replace fossil fuels equivalent to more than 1,000 kg CO_2-eq per ton of PME. The net CO_2-eq emissions saving by implementing the improved residue use is thus about 2,000 kg CO_2-eq per ton of PME without allocation to non-PME coproducts. That is equivalent to the total CO_2-eq emissions from PME production without inclusion of the contribution from residues. The potential carbon sink of the improved residue use is substantial enough to make the production of PME close to GHG neutral not including the contributions from LUC.

Hansen et al. (2012) allocate emissions by mass to four coproducts: PME, palm kernels, palm fatty acid distillate (PFAD), and glycerin, resulting in a total mass allocation of 33 % to non-PME coproducts. In order to be able to compare the results in this study with the results in EU-RED, allocation should be done by energy content, whereby only 26 % is allocated to non-PME coproducts in accordance with Appendix A in the Electronic Supplementary Material. The land use change emissions presented in this study will follow

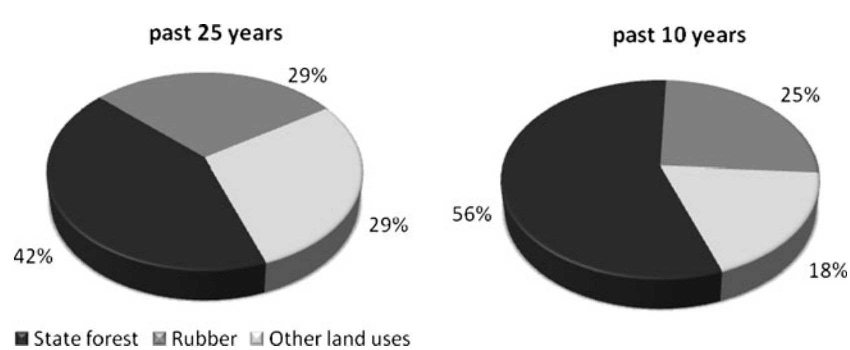


Fig. 1 Conversion of land to oil palm plantations

the same 26 % energy allocation. However, in order for this study to comply with the state-of-the-art LCA methodology (see Section 2.1), some variations occur compared to the methodology of EU-RED. Hansen et al. (2012) take the substitution of fossil fuels by the residue use into consideration. EU-RED does not recognize residue use benefits unless the residues have a market value, in which case they are considered coproducts and dealt with through allocation. EU-RED also does not recognize other consequential LCA methods such as indirect land use change (ILUC) or induced emissions, nor the distinction between fossil and biogenic carbon. Appendix B in the Electronic Supplementary Material describes a scenario and derived results of this study adhering to the EU-RED methodology.

2 Methods

2.1 Life cycle methodology

The life cycle methodologies used in the study follow or are derived from ISO 14040 as presented in the ILCD Handbook (European Commission 2010). The methodological choices are listed below.

- Impact time horizon: 100 years.
- Biogenic carbon and temporary carbon storage: In LCA, the temporary uptake of biogenic carbon in biomaterials and plants (e.g., plantations) is by default not credited as it is insignificant in the infinite impact time horizon applied in conventional LCA (European Commission 2010). However, when applying a 100-year impact horizon, which is commonly done for global warming impacts, the temporary storage can be significant and temporary carbon storage may be included as is done in this study. In such cases, the ILCD Handbook (European Commission 2010) credits 1 % of the total stored carbon per year of storage (i.e., full credit is given if the carbon is stored for 100 years or more).
- Fossil carbon: As carbon in virgin forests has been in equilibrium for thousands or millions of years, the carbon stored in these forests is considered permanently stored and is termed as fossil carbon (e.g., European Commission 2010). The fraction of carbon left in the logged-over state forest reserve after timber harvest and thus the emissions from the conversion to oil palm are considered fossil carbon emissions as well. The emissions from the biomass added during the potential recovery of the forest and in the oil palm plantations are considered biogenic.
- System time horizon: All emissions from land conversion to a plantation are allocated to the first generation of the plantation use (European Commission 2010). So in this study, only plantations established within the past 25 years are considered as contributing to land use change impacts. Soil carbon takes more than 25 years to establish a new equilibrium, but the estimated total emissions are allocated to the first generation of plantation. By including emissions for all first generation plantations, LUC emissions, which happened up to 25 years ago, are included in the average Malaysian LUC emissions (see Section 3.1.6). From a legislative point of view, such emissions cannot be included as the awareness of the impacts had not surfaced at the time and palm oil producers cannot be held responsible. However, from a strictly scientific point of view, the emissions have occurred, and it is argued that the palm oil/PME produced on the land has to pay off the incurred carbon dept. The impact of only including LUC since 2008 as done in EU-RED (European 2009) is tested in the sensitivity analysis.
- This study focuses on describing the LUC impacts from the average Malaysian scenario. However, individual LUC data for the Malaysian state forest reserve and rubber plantations are presented as well in order to determine the main sources of emissions.

3 Results and discussion

3.1 Land use change emissions

Land use change data used in this study are presented briefly in Sections 3.1.1, 3.1.2, 3.1.3, 3.1.4, and 3.1.5. Additional details and input data for emission calculations as well as further references can be found in Appendix C in the Electronic Supplementary Material.

3.1.1 Oil palm plantation

A fully grown oil palm plantation holds approx. 90 t biomass per ha (derived from Germer and Sauerborn (2008); Khalid et al. (1999a, b)) with a carbon content of 42 % dry weight (Chow et al. 2008), equalling sequestration of 140 t $CO_{2,b}$-eq/ha. As the biomass builds up approximately linearly over 25 years, the average storage time is 12.5 years, which in accordance with Section 2.1 justifies a credit of 12.5 % of the sequestered CO_2. The credit for an oil palm plantation is thus 17 t $CO_{2,b}$-eq/ha per plantation cycle. If plantation residues are used in a manner, which stores the carbon or replaces fossil fuels, then carbon credits should be given for the use, but such credits do not belong under LUC. See, e.g., Hansen et al. (2012) for residue use calculations.

In accordance with Germer and Sauerborn (2008) and Mathews et al. (2010), the soil carbon content in an oil palm plantation on mineral soil is set to 80 t C/ha.

3.1.2 Malaysian state forest reserve

Forest conversions to oil palm plantations in Malaysia only take place on state forest reserve land, which is always logged for timber prior to land conversion. When logged through selective logging, a tropical forest of approx. 340 t biomass/ha and 50 % dry weight carbon content (Germer and Sauerborn 2008) loses about 45 % of the standing biomass (Lasco 2002), bringing it down to a total of approx. 190 t biomass. The carbon loss, which is equivalent to 280 t $CO_{2,f}$-eq/ha is allocated to the timber. When clearing the logged-over forest to establish an oil palm plantation, the organic litter from the clearing is left to degrade partially at the cleared site as mulch or in the surrounding land. Due to a lack of emission data during the degradation, Germer and Sauerborn (2008) assume full conversion of organic carbon to CO_2. This methodology is applied in this study as well. The emissions from clearing of logged-over forest thus emits 350 t of fossil CO_2 equivalents ($CO_{2,f}$-eq) per hectare. Had the logged-over forest been left idle, it could on average likely have recovered to approx. 240 t biomass/ha within the 25-year system time horizon of this study (derived from Silver et al. (2000)). By clearing the forest, the 50 t biomass, equalling 90 t biogenic CO_2 equivalents ($CO_{2,b}$-eq) per hectare that would have been sequestered thus stay in the atmosphere and are allocated to the land use change. Some logged-over forest will be cleared shortly after logging, while other may stand (and recover) for decades. The 25-year time horizon of this study is assumed to be a suitable average. Thus the "missed" temporary carbon storage credit is given 12.5 % credit as for the oil palm plantation resulting in an indirect emission of 12 t $CO_{2,b}$-eq/ha.

No studies have been identified, which quantify the soil carbon in a logged-over forest. This study assumes that the soil carbon is somewhere between the 120 t C/ha in a virgin forest (Germer and Sauerborn 2008) and an oil palm plantation. In a lack of better data, the soil carbon in the state forest reserve is estimated at 100 t/ha. The conversion to oil palm thus results in a loss of 20 t soil carbon per ha, equalling 70 t $CO_{2,f}$-eq/ha. The sensitivity of this assumption is tested in the sensitivity analysis.

The net emissions from the conversion of the Malaysian state forest to oil palm are thus 350 t $CO_{2,f}$-eq plus 70 t $CO_{2,f}$-eq/ha from soil carbon depletion, equalling 420 t $CO_{2,f}$-eq. The net temporary carbon storage is plantation sequestration of 17 t $CO_{2,b}$-eq minus the missed recovery storage of 12 t $CO_{2,b}$-eq, equalling 5 t $CO_{2,b}$-eq/ha.

The variation in the literature data are accounted for in Appendix C in the Electronic Supplementary Material, and the sensitivity is quantified in the sensitivity analysis.

3.1.3 Rubber plantations

The sequestered biogenic CO_2 in biomass in a rubber plantation just before felling is approx. 260 t C/ha (Yew 2001) or almost double the amount of carbon in an oil palm plantation. Rubber plantations have a planting cycle of 25 years, which as for oil palm gives a temporary biogenic carbon storage credit of 12.5 %, resulting in 33 t $CO_{2,b}$-eq/ha. Thus, the loss from conversion to oil palm is 16 t $CO_{2,b}$-eq/ha. The literature suggests that soil carbon content in rubber and oil palm plantations is similar (e.g., Lai (2004)), so the loss/gain in conversion from rubber to oil palm is set to 0.

When converting a rubber plantation to an oil palm plantation, the rubber that was produced at that plantation must be produced somewhere else, assuming that the world rubber demand is unchanged. In this study, it is assumed that the rubber is produced synthetically from fossil oil, thus creating induced emissions. Please see additional discussion in Appendix C in the Electronic Supplementary Material. Patel (2003) reported cradle to gate emissions from production of synthetic rubber of 1.38 t CO_2-eq/t of rubber in Germany. Additionally, there is fossil carbon equivalent to 3.3 t CO_2/t of rubber (styrene–butadiene rubber) stored in the synthetic rubber, which will be released upon disposal of the rubber product, giving a total of 4.7 t CO_2-eq per ton of rubber. As for comparison, Jawjit et al. (2010) reported an average of 0.65 t CO_2-eq/t of natural rubber produced in Thailand. The net additional emission from producing synthetic rather than natural rubber is thus 4.1 t CO_2-eq/t of rubber, which, with 0.9 t of rubber produced per hectare per year in Malaysia (MRB 2011), equals 3.7 t $CO_2\,ha^{-1}\,year^{-1}$ by producing the rubber synthetically. Over a 25 year plantation cycle that amounts to approx. 94 t CO_2/ha are assumed fossil.

In summary, there are net emissions of 94 t $CO_{2,f}$/ha and 16 t $CO_{2,b}$-eq/ha from conversion of rubber to oil palm.

3.1.4 Other land uses

No references have been identified, which specify the specific nature of other previous land uses. According to the Malaysian Department of Statistics (JPM 2012), the main agricultural decliners in terms of area are fruits, coconut, and cocoa. It can thus be assumed that these are the crops giving way to oil palm plantations. According to Wulan et al. (2012), coconut and cocoa have biomass carbon stock of about 30 t C/ha, which is lower than the 37 t C/ha in the oil palm biomass. However, due to the temporary nature of the biogenic sequestration, the credit to oil palm is less than 4 t CO_2/ha. This small change in carbon stock and the uncertainty of which specific crops are displaced have led to the conversion of "other land uses" to be omitted from the study, i.e., the conversion is considered carbon neutral. The scenario with a net sequestration of 4 t CO_2/ha for other land uses has been tested in the

sensitivity analysis. Additionally, there is the matter of indirect land use change (ILUC) when a crop is replaced. ILUC is not included in the scope of this study but has been included in the sensitivity analysis.

3.1.5 Peat

Seven to eight percent of Malaysia is covered by peatlands, and just below 15 % of the oil palm plantations in Malaysia are planted on peat, mainly in Sarawak (Wahid et al. 2010). Peatlands are perhaps the most controversial of the land uses, and numerous studies have highlighted that draining peatlands for agricultural development will lead to very large soil CO_2 emissions through oxidation of the exposed peat, e.g., Page et al. (2011); Couwenberg et al. (2010). However, some recent studies have indicated that the models used to calculate these emissions are not representatives for tropical peat and that emissions from well-managed plantations on peat soils may not be significant. Melling et al. (2005) and Melling et al. (2012) have shown that soil CO_2 emissions can even be higher in tropical virgin peat swamp soils than in drained and compacted plantation peat soil. Although the additional emissions are likely from higher biogenic litter degradation and root respiration in the virgin peat (Melling et al. 2012), it shows that the compacted cultivated peat is not necessarily a higher carbon emitter than virgin peat swamps. Melling et al. (2012) highlight that due to the heterogeneous characteristics of tropical peatland, further studies on, e.g., environmental factors, peat properties, and microbial activities are necessary to reach firm conclusions. Thus, due to insufficient data and understanding of peat, this study has chosen to omit peat from the assessment. Conventional peat emission estimations have been included in the sensitivity analysis in Section 3.3.

3.1.6 Malaysian average LUC emissions

Figure 2 summarizes the GHG emissions for land conversion to oil palm plantation in Malaysia derived from Sections 3.1.1, 3.1.2, 3.1.3, and 3.1.4, with positive values being emissions and negative values being sequestration. For the "national oil palm land use change emissions," the relative land use change contributions from Fig. 1 for the past 25 years are used with the inclusion of temporary carbon sequestration by the fraction of plantations planted more than 25 years ago (second generation or older). In order to simplify the presentation and further use of the results, no distinction is made between biogenic and fossil carbon in the total values for each LUC and for the national average, but the contribution from the biogenic sources is subjected to multiplication by 12.5 % as per Sections 3.1.1, 3.1.2, 3.1.3, and 3.1.4. As per Section 1, this study argues that the national oil palm land use change emissions should be used in environmental assessments of PME.

The LUC emissions allocated to oil palm plantations are the values of the arrows pointing directly at "oil palm plantation" in Fig. 2. Thus, as per Section 3.1.2, the emissions from "primary forest" to "logged forest" are not allocated to the oil palm plantations. As only 30 % of the current oil palm plantations in Malaysia are first generation plantations planted on former logged forest, only 30 % of the logged forest conversion emissions, i.e., 125 t CO_2-eq/ha, are contributing to the Malaysian average. The same is the case for rubber plantation conversions, second generation oil palm plantations, and other former land uses.

Each generation of oil palms collects temporary carbon credits. Thus, the plantations of second generation and older receive the credit without having LUC emissions. It is clear from Fig. 2 that the state forest reserve conversion is in fact the only significant direct LUC, as the temporary carbon storage in the rubber plantations only counts little in the overall carbon balance. When including induced emissions from synthetic rubber production, the LUC contribution from rubber becomes noticeable, but it is still much preferred to state forest reserve conversion from a carbon emission point of view. ILUC from rubber or other crops could, however, be significant as will be shown in the sensitivity analysis.

3.2 Land use change impacts in relation to biodiesel life cycle

It takes 0.26 ha to produce 1 t crude palm oil per year based on average Malaysian yield for 2007–2011 (MPOB 2012) and 1.09 t crude palm oil to produce 1 t PME (Choo et al. 2011), thus resulting in 0.28 ha to produce 1 t PME/year. In order to be able to compare the impacts from land conversion to oil palm with the impacts from the PME production, the LUC emissions are related to a reference flow of 1 t PME. With an LUC emission time horizon of 25 years (see Section 2.1), the area needed to produce 1 t of PME over the duration of the time horizon is 0.011 ha. The LUC emissions are thus multiplied by 0.011 ha.

In Table 1, the land use change emissions presented in Fig. 2 are subjected to the 26 % energy allocation to non-PME coproducts and added to the PME production emissions. It is evident that for conversion of the Malaysian state forest reserve, the emissions are so large that PME production on such lands will result in emissions larger than emissions from fossil diesel throughout the first plantation generation. In fact, with conventional PME production it will take the most of a century before the PME has net greenhouse benefits. Even with improved/optimized production, almost 40 years will pass before a net reduction in emissions can be seen. On the contrary, conversion from rubber plantations has very limited impacts. The national average emissions for PME production including LUC as presented in Table 1 can meet the EU-RED criteria of 55 g CO_2/MJ (European 2009), but the success depends on the manner in which the PME is produced. Also, it

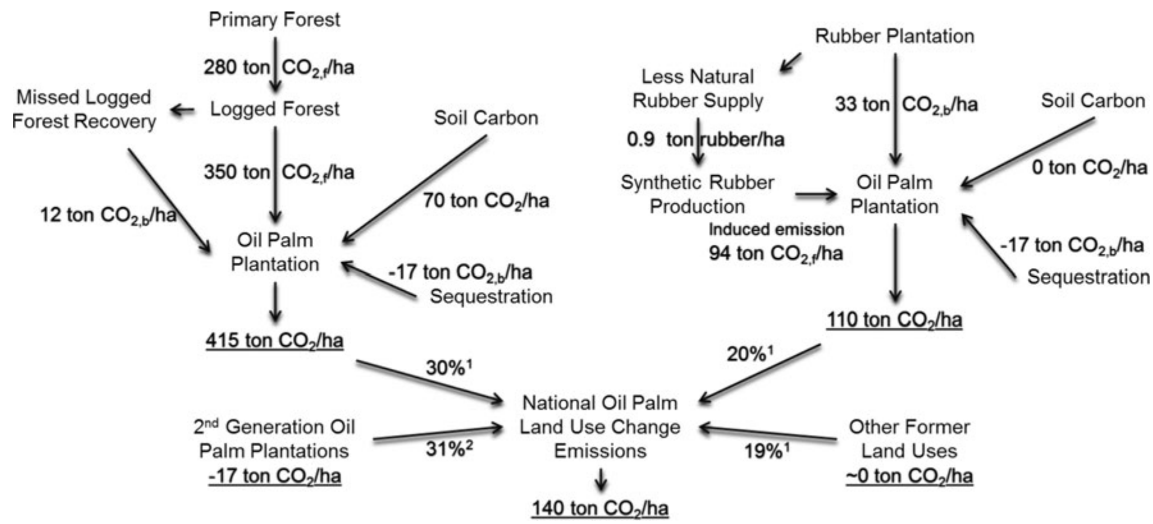


Fig. 2 GHG emissions for land conversion to oil palm plantation. CO_2 values given are CO_2-eq. Refer to Sections 3.1.1, 3.1.2, 3.1.3, and 3.1.4 for data background and calculations. *1* Percentage of first generation oil palm plantations planted on the respective former land uses out of total oil palm planted area in Malaysia. *2* Percentage of second generation or older oil palm plantations out of total oil palm planted area in Malaysia

must be noted that from 2017, the EU-RED criteria will be lowered to 42 g CO_2/MJ, which is 50 % of the emissions from fossil diesel (European 2009).

With the conventional waste treatment presented in Hansen et al. (2012) (see Section 1), an almost 90 % reduction in the Malaysian average LUC emissions is required to meet the EU-RED requirements, whereas an increase of about 20 % in LUC is permitted if the improved waste treatment from Hansen et al. (2012) is implemented nationwide. With a 50 % implementation rate of the improved waste scenario presented by Hansen et al. (2012), a 33 % reduction in the LUC emissions is needed, whereas 80 % nationwide implementation of the improved waste scenario is required for PME to be labeled renewable if the current LUC emissions are maintained.

The updated LCA methodology used in this paper makes it difficult to compare the LUC results with conventional studies. Wicke et al. (2008) also assess LUC from logged-over forest. Whereas the emissions from the felling of the logged-over forest are similar in the two studies, Wicke et al. (2008) arrive at a lower net LUC impact of 50 g CO_2-eq/MJ as full credits are given to sequestration in the oil palms. On top of that, Wicke et al. (2008) use carbon stock data for the oil palm plantation, which are significantly higher than the ones used in this study by Germer and Sauerborn (2008) and Khalid et al. (1999a, b). It is argued that previous studies such as Wicke et al. (2008) are underestimating the LUC impacts by disregarding the temporary nature of the oil palm sequestration. On the other hand, the studies by Reijnders and Huijbregts (2008) and Danielsen et al. (2009) do not take into consideration that the forest is logged prior to oil palm conversion, which, at an equivalent of 160 g CO_2/MJ, overestimates the LUC emissions for the Malaysian scenario. Thus, the accounting methodology is of utmost importance. Targeting degraded (low carbon) land for oil palm plantations means that there will be a net carbon sequestration and that no ILUC occurs. Planting oil palm on degraded land will result in net carbon sequestration of 135 t CO_2/ha, including biomass and soil carbon (Germer and Sauerborn 2008), which, when applying the 12.5 % temporary carbon storage, credits amount to 17 t $CO_{2,b}$-eq/ha. This corresponds to a net sequestration of only 5 g CO_2/MJ of PME produced, on top of which degraded land is likely to result in lower oil yield. Degraded land should thus not be targeted because of the prospects of carbon sequestration but rather because the alternatives—forest or other agricultural crops—can result in large emissions through direct and indirect LUC.

Aside from the quantitative emissions associated with palm oil-related LUC, there are ongoing debates on the rights of, e.g., Malaysia and Indonesia to develop their land and boost their economies, e.g., Padfield et al. (2011). It could be argued that a certain leeway on the LUC emissions could be given from a political and social point of view; however, from a scientific and environmental standpoint, the impacts of state forest reserve clearings remain as presented in this paper.

3.3 Sensitivity

A sensitivity analysis has been prepared by quantifying impacts on the Malaysian national oil palm LUC emissions from variations in the data and assumptions made in this study. The results are presented in Fig. 3 along with potential future scenarios. The biggest sensitivity variable is plantations on peat. Assuming that 75 % of the plantations planted on peat are planted in the past 25 years and applying emissions of

Table 1 CO_2-eq emissions from LUC and PME production emissions

	Oil palm on the state forest reserve[a]	Oil palm on a rubber plantation[b]	Malaysian average emissions[c]	
LUC emissions	415	110	140	ton CO_2/ha
	126	33	43	g CO_2/MJ
LUC emissions with 26 % energy allocation to coproducts	304	80	104	ton CO_2/ha
	93	24	32	g CO_2/MJ
Conventional[d] PME (no LUC emissions)	–	–	48	g CO_2/MJ
Improved[e] PME (no LUC emissions)	–	–	3	g CO_2/MJ
Conventional[d] PME incl. LUC emissions	140	72	79	g CO_2/MJ
Improved[e] PME incl. LUC emissions	95	27	34	g CO_2/MJ
LUC emission payback time[f] (conventional[d] PME)	64	17	22	years
LUC emission payback time[f] (improved[e] PME)	28	7	10	years

[a] Emissions for PME derived from plantations planted on Malaysian state forest reserve

[b] Emissions for PME derived from plantations planted on former rubber plantation

[c] Malaysian average emissions for PME production as per land use distribution in Fig. 3

[d] Conventional PME production as presented in Hansen et al. (2012) but subjected to 26 % energy allocation to coproducts

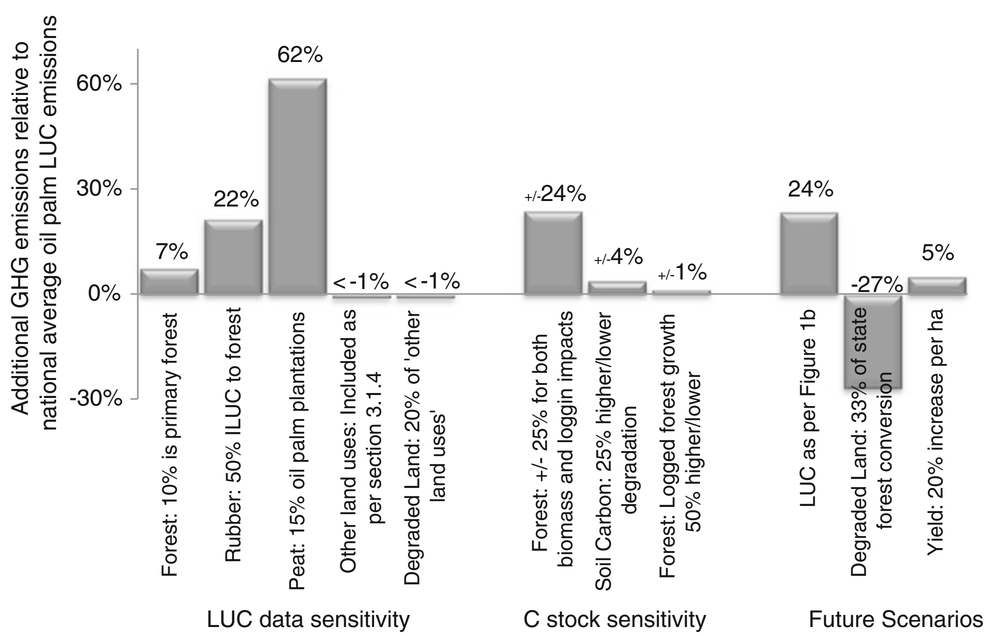
[e] PME production including the improved residue use presented in Hansen et al. (2012) but subjected to 26 % energy allocation to coproducts

[f] As defined by Fargione et al. (2008) and Gibbs et al. (2008)

800 t CO_2/ha over 25 years (Germer and Sauerborn 2008), the national oil palm LUC emissions are increased by more than 60 %. It is thus of very high importance that the actual emissions from oil palm plantations on peat are quantified by representative experimental data.

Another significant variable is the inclusion of ILUC in the conversion of rubber plantations. In Fig. 3, half of the rubber from plantations, which have been converted to oil palm, are replenished by establishing new rubber plantations through directly or indirectly converting an equivalent of the Malaysian state forest reserve in other tropical countries. The actual consequences of replacing rubber plantations should thus be investigated. Such significant impacts could occur in relation to replacement of other crops than rubber as

Fig. 3 Sensitivity analysis and future scenarios



well. However, without the inclusion of ILUC, the inclusion of “other land uses” into the assessment seems to be insignificant whether the other land uses are crops or degraded land.

The assumption that all forest converted to oil palm is a state forest reserve and would be logged, i.e., large trees being taken out, in any case whether or not the oil palm plantation is established, should stand firm. The sensitivity analysis shows that if a small part of the forest (here, 10 %) is in fact not harvested for timber, e.g., because it is too far from existing infrastructure to make timber transport feasible, then although it does have significant site-specific impacts, it does not have much influence on the national average LUC emissions. The accuracy of data on biomass in the state forest reserves and the biomass removal through logging does, however, have high impact. More data on site/regional ranges of biomass and the influence of logging are thus much needed.

The three future scenarios in Fig. 3 are all based on the LUC ratios presented in Fig. 1 for the last 10 years. The increased forest conversion will result in higher emissions. However, two ways of curbing this development are by ensuring that the yield is increased, thus limiting the need for oil palm expansion or by using biochar from oil palm residues to regenerate degraded land (Roberts et al. 2010) and use this land for oil palm expansion rather than converting state forest reserve. Increasing the yield alone will reduce the increase in emissions, but it is not sufficient to reduce emissions to below the level of the current national average LUC emission in Fig. 2 and Table 1 unless other actions are taken as well. However, targeting the one million ha of degraded land in Malaysia (Wicke et al. 2011) rather than state forest reserve does have huge potentials for reducing the LUC, even on its own. Action is required immediately as it will take several years of planting on degraded land rather than on forest before a significant relative reduction of oil palm plantations on former state forest reserve can be seen in the Malaysian average land use picture. In this context, it should, however, be noted that degraded land is not necessarily without value to local communities and that displacement of local community activities could result in ILUC if proper stakeholder involvement in the planning process is not undertaken (Findlater and Kandlikar 2011).

Following the LUC methodology of EU-RED, which is also practiced by conventional LUC studies (e.g., Germer and Sauerborn 2008), the Malaysian average LUC emissions over 25 years decrease by 12 %, mainly due to the full carbon storage credits in the oil palm plantations. However, as EU-RED only includes LUC after 2008, the reported average Malaysian LUC emissions actually decrease by 86 %. In other aspects like residue use, the EU-RED methodology is, however, less favorable for palm oil. See Appendix B in the Electronic Supplementary Material for more details. If the Malaysian average LUC emissions presented in this study were subjected to the 2008 cutoff point, the emissions would be reduced by 88 %, which highlights the impacts of political decisions on such results.

4 Conclusions

Land use changes contribute significantly to the CO_2 emissions from production of PME and result in long payback times if the previous land use is high-carbon stock land like the state forest reserve. The average PME production is also significantly influenced by LUC. Due to the temporary nature of the biogenic carbon sequestered in oil palm plantations, these can only offset relatively few LUC emissions. Whereas the net emissions from rubber conversion to oil palm are relatively small, the emission can potentially increase significantly if ILUC is included in the assessment. Thus, although the sequestration benefits of converting degraded land are small, it is much preferable to the conversion of other land from an environmental perspective. The option of restoring and using degraded land should thus be investigated. It is clear that with a combination of avoiding forest conversion and implementing environmental optimization of the palm oil and PME production, Malaysian palm oil can be environmentally sustainable from a global warming point of view.

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